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THE APPLICATION OF FLIGHT AND SIMULATOR TESTING TO VTOL AIRCRAFT HANDLING QUALITIES SPECIFICATIONS

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INTRODUCTION

~~Although some specific problems remain unsolved,~~ General V/STOL handling qualities research ~~has been essentially completed through the use of~~ with various simulators and test aircraft~~. The purpose of this research was~~ is sufficiently complete to provide guidance to the aircraft designer ~~and to assure that a given vehicle's handling qualities would be acceptable to the pilots~~. Since several pre-production prototype V/STOL aircraft have been completed and others are nearing the flight test stage, considerable effort is being expended to adapt the research results to written specification for this class of aircraft. ~~Because~~ There are ~~such~~ a great variety of V/STOL types and different ~~our knowledge of the~~ problems are introduced by each ~~is obviously incomplete~~. Nevertheless, it is important to translate as much of the research experience as possible into handling qualities specifications at an early date. The purpose of the specifications is to give the operator some assurance that the mission capabilities of the aircraft, when it is delivered, will not be unduly limited by its handling qualities and that the aircraft can effectively perform the mission for which it was designed.

The handling qualities requirements necessary to allow vertical take off and landing for aircraft which differ radically from helicopters have been the subject of numerous investigations and an extensive bibliography would be required to list all of them. However, even research data obtained while hovering under visual conditions are difficult to translate into meaningful specifications.

A review of the tests indicates apparent differences between simulator results and even between flight test data as obtained by different researchers.

Very little is to be gained by trying to resolve all of the differences in results especially when flight and simulator data are compared. However, if we consider that the simulators have assisted in directing us to the important variables and then look at the flight test results as being more definitive, we see that we have come a long way towards defining the acceptable limits of several important control parameters for the visual hovering task. The development of VTOL aircraft other than helicopters has made it necessary to consider values of control power and rotary damping which were not always germain to helicopter designs and yet are of primary importance to the VTOL aircraft. The rotary wing provides inherent pitch and roll damping and relatively high control powers are obtained without sacrificing performance. However most VTOL aircraft will have very low rotary damping about one or more axes without stability augmentation and it has been difficult to design VTOL aircraft to the values of control power which were in most cases readily obtained on helicopters.

Several well defined handling qualities limitations were encountered during the flight tests of the X-14A research airplane and several other VTOL aircraft while hovering in visual flight conditions. The purpose of this paper is to describe some of these limitations and to compare the results with the available specifications for VTOL airplanes. ( )

-14 RESULTS

Description of aircraft:- The basic X-14 airplane shown in figure 1 was modified by the NASA to provide it with increased thrust, variable control power and variable angular rate damping about all three axes. This VTOL airplane is powered by two General Electric J-85-5 engines of 2200 lbs. thrust with cascade

diverters in the exhaust exits which allow the thrust to be vectored 90° to the engine rotational axis for hovering flight. Dual reaction control jets at the wing tips and at the tail are supplied with engine compressor bleed air to provide control moments while hovering and in very low-speed flight. One set of nozzles is mechanically connected to the control stick and rudder pedals and the second set is servo operated in response to signals from rate gyros and the pilot's control position inputs through cockpit mounted potentiometers which allow independent variation of control power and damping about all three axes. Additional circuitry is provided to cancel the engine gyroscopic moments. Further details of this airplane and its control system are described in references 1 and 2.

Five pilots have flown this airplane through a wide range of control power and damping characteristics and their opinions expressed in the Cooper rating scale were reported in TN D-1328. The task involved was simply visual hovering which includes accelerating to about 20 knots in all directions in relatively light winds. For this reason the control power-damping boundaries obtained are very close to a minimum operational requirement. The boundaries for control response about all three axes for the visual hovering task are shown in figure 2. The 6.5 boundaries for each axis were determined in flight to be the minimum safe values of control power and damping even under the nearly ideal test conditions. Several accidents and near accidents which have occurred with several test bed aircraft when operations were conducted beyond (with lower control powers) than the limiting values presented in this figure. It should be mentioned however that the yaw axis was the least critical from the safety point of view during these tests.

COMPARISON WITH MIL-H-8501A

In order to transform the results presented in reference 2 into handling qualities specifications it is generally necessary to express them in a simpler form. One form that has been used is the helicopter Military Specification MIL-H-8501A for hovering control response. This specification allows a direct reduction in control response with aircraft weight and a reduction in rate damping as a function of the appropriate moment of inertia. A comparison of the specification for roll response and the data obtained from the X-14 flight tests is shown in figure 3. The present roll response requirement in reference 3 is $96/(W+1000)^{1/3}$ degrees in 1/2 second; however, a requirement for lateral displacement after one second equal to or greater than $300/(W+1000)^{1/3}$ degrees has been proposed and this response requirement is shown in figure 3. Since the X-14 weighs 3800 pounds the roll response required by this specification for this airplane falls in an area which was determined from flight test to be acceptable for only limited operation for an aircraft of this weight.

The addition of the specification roll damping requirement of $25(I_x)^{0.7}$ ft lb/deg/sec still would provide only limited operational capability according to the flight test results.

During the development of this aircraft it was found to be necessary to increase the lateral control power from slightly less than 1 radian/sec^2 to almost 2 rad/sec^2. Some adjustments were made to the control sensitivity which improved the controlability but satisfactory lateral control was not obtained until the aircraft was provided with the higher control power.

It is obvious that the helicopter specifications (ref. 3) which emphasizes the weight of the aircraft in determining its control power do not agree with the available VTOL aircraft test information for the roll axis.

A comparison of the helicopter specification for longitudinal response while hovering also indicates an inconsistency with the flight test results reported in reference 2. This comparison is shown in figure 4. In this case, however, the military specifications requires considerably more response for a 3800 lb. aircraft such as the X-14 than the test results indicate is necessary for normal operation.

The level of damping augmentation required is much higher than is required for visual hovering as it also was for the roll axis. This level of damping might very well be required for certain missions but the specification appears to require this value for all normal operations.

The results of the X-14 stability and control flight tests also indicate (figure 4) that, given adequate control power, visual hovering operation can be conducted even with zero rate damping about any axis and with only the basic airplane damping (no damping augmentation) about all axes simultaneously. Flights in a 12,000 lb. vectored thrust VTOL strike fighter also verified that the damping level provided by the basic airplane need not be augmented and, in fact, experience has shown that the control power and damping requirements for VFR hovering about all axes were the same for this 12,000 lb. aircraft as they were for the X-14 which weighed one-third as much. Two direct conclusions can be reached from these flight tests in the 4,000 lb. to 12,000 lb. range. First, the basic airplane rotary damping is sufficinet for vertical take off - landing and other VFR hovering operations. Second, no reduction in the control power required for normal operation was found due to the three-fold increase in weight although the specification for roll control power (fig. 3) indicates that a 30 percent reduction in the

X-14 test values should have been adequate. The lower values were tried on the heavier aircraft and found to be insufficient. For these reasons it is believed that the reductions in control power with increased weight allowed by the present specification could be misleading to the designer of very heavy VTO aircraft. Several flight test experiments are being developed which it is hoped will provide us with more definitive results but they are complicated by the very large changes in weight which apparently will be required in order to detect a change in the control requirements. It is of interest to note that ground simulators are of little value in this area. At this point it is tempting to shift our rationalization to a size or linear measurement instead of the weight effect but again experimental results are not available for the hovering case.

These apparently very high control power requirements leave the designer of a future 100,000 lb. VTO aircraft in somewhat of a quandry since at this gross weight and size the moments of inertia will be so high that the thrust required for control moments is often an undesirable large percentage of the thrust required for lift. Furthermore, the cost of such a venture is so high that a purely experimental aircraft is out of the question. An approach which has been suggested is to build a large frame work in the form of a cross having lift and control engines mounted at the end of each arm. It is possible that significant information could be obtained from limited hovering tests to determine the influence of size and inertia on the control response requirements by this method. It is easy to dismiss this scheme out of hand; however, in the light of the results obtained to date an effort of this type may be required to provide guidance to the designer of very large VTOL aircraft.

The total control power and rotary damping requirements have been emphasized because of their importance in meeting the response specified in references 2 and 3.

Other control conditions of course are important when overall handling qualities are considered and flight test data are available which show the need for optimizing control sensitivity, i.e., control power per inch of control displacement, reference 4, and the velocity stability parameter Mu as reported in reference 5.

The flight tests of reference 5 shows that neutral velocity stability is the most desired condition when in near hovering flight and that increases in velocity stability not only increase the pilot's control task but the moments produced by velocity also reduce the control power available for maneuvering. Small errors in predicting the velocity stability of a VTOL aircraft can easily subtract from the control power available for maneuvering therefore the levels or control power found to be required from the X-14A flight tests are in excess of the requirements to trim moments produced by stability and engine power changes.

Height control:- In addition to the need to control pitch, yaw, and roll of the VTOL aircraft the pilot must also control height which becomes independent of pitch attitude and dependent on thrust response as hovering flight is attained. Studies of height control requirements such as reported in references 6 and 7 were conducted on simulators and provide an indication of the influence on pilot opinion of the important height control response parameters. Increases in both available thrust-weight ratio and damping from near zero levels were found to be desired and a collective type height control sensitivity of about .1g per inch approached the optimum value. The minimum levels of T/W and height rate damping were difficult to define because they appeared to be so much a function of the hovering task requirements. During recent studies using the Ames Height Control Simulator, values of control power of less than 1.15g and zero height rate damping still

allowed the hovering steadiness requirements of reference 3 to be met even though the ability to change height and stabilize quickly had deteriorated. The one parameter which resulted in a decrease in hovering steadiness and which created a dangerous height control situation was a large increase in the first order response of thrust to a step height control input.

The simulator which was used to investigate the effects of the thrust response time constant is shown in figure 5. The cab travel is 100 feet, maximum velocity ±20 feet/sec., accelerations of ± 96 ft/sec^2 can be attained. The cab height is controlled by a collective lever and the desired levels of response are provided by an analogue computer. The results of the tests of the thrust time constant are shown in figure 6 which shows the variation in pilot rating (Cooper Scale) with increases in the time constant. They were based on the hovering steadiness requirements of reference 3. That is to hold height ± 1 foot with 1/2 inch or less of collective motion. A total T/W of 1.15 was provided and the collective sensitivity was .1g per inch. The height rate damping was zero which represents a more severe condition than most VTOL aircraft would have. Increasing the time constant from zero to .3 second caused a noticeable decrease in hovering steadiness. A value of .6 second caused over-controlling and a value of 1.2 seconds required nearly full pilot attention. Neither condition met the specification for hovering steadiness. A time constant of 2.4 seconds resulted in a dangerous situation, large excursions in height occurred and the pilots indicated that no attempt at flight should be made with this condition.

The time histories of height control input and cab response for several test conditions are shown in figures 7 to 11.

The requirements for hovering steadiness of reference 3 are indicated on the figures as dashed lines. When essentially zero time constant is present all the requirements are readily met as is shown in figure 7. A thrust response time constant of .3 second results in a noticeable increase in collective stick motion but still less than the ± 1/2 inch allowed. Height rate exceeded 2-1/2 feet per second by a small amount however on the run illustrated in figure 8 height was maintained within a few inches. At .6 second all three steadiness requirements were exceeded or had reached the specification limits. Further increases in the thrust response time constant resulted in a general decrease in hovering controllability which is shown in figures 9 - 11. The pilot opinion variation with this time constant shown in figure 6 indicates that a maximum of .45 seconds is the limit for normal operations but .3 seconds is required to meet the existing specifications.

CONCLUDING REMARKS

Flight test data has been presented which defines the VFR hovering control power requirements for VTOL aircraft in the 4,000 lb. to 12,000 lb. weight class. There are large differences between this data and the present military specification for helicopters. No significant differences in the control power requirements were noted with a three-fold change in aircraft weight although the existing specification allows a 30 percent reduction at the higher weight. The tests indicate that further investigations will be required at much higher weights and with larger hovering test vehicles in order to provide more realistic guidance for the designer of very large VTOL aircraft.

More than 10 pilots have flown the X-14A jet lift VTOL aircraft with zero rate damping about each axis and with just the basic airplane damping about all axes

simultaneously. Their comments indicate that given adequate control power the unaugmented airplane is satisfactory for visual hovering operations. A brief investigation of height control response on a moving base simulator indicated that hovering steadiness is markedly effected by the first order thrust response time constant. The pilots felt that only limited operation should be attempted with a thrust response time constant in excess of .4 second and that operation with a time constant exceeding 1.2 seconds will be dangerous. These limitations are in agreement with the hovering steadiness requirements of the military specification for helicopters.

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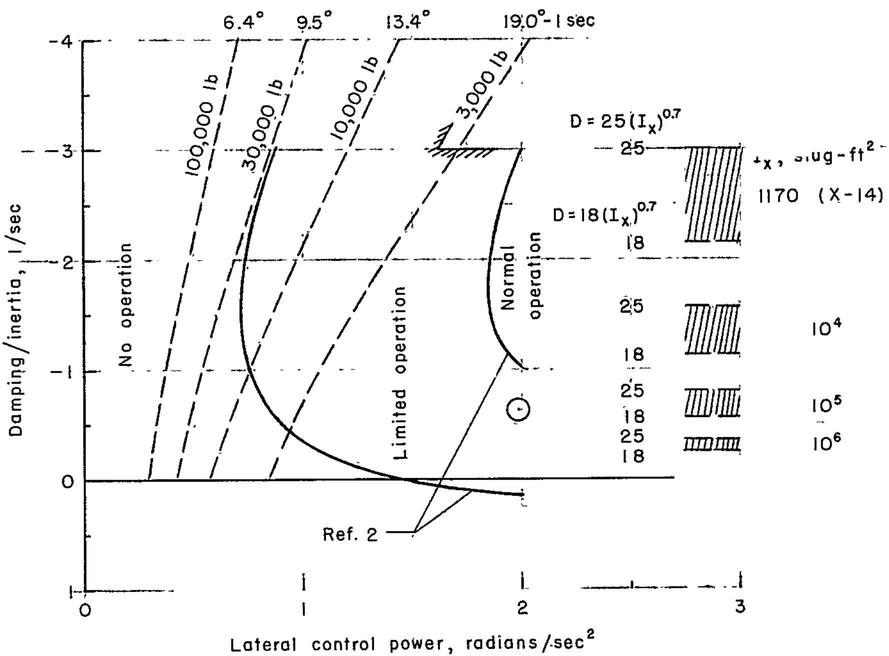

Figure 3.— Comparison of flight test results with MIL-H-8501A for the roll axis.

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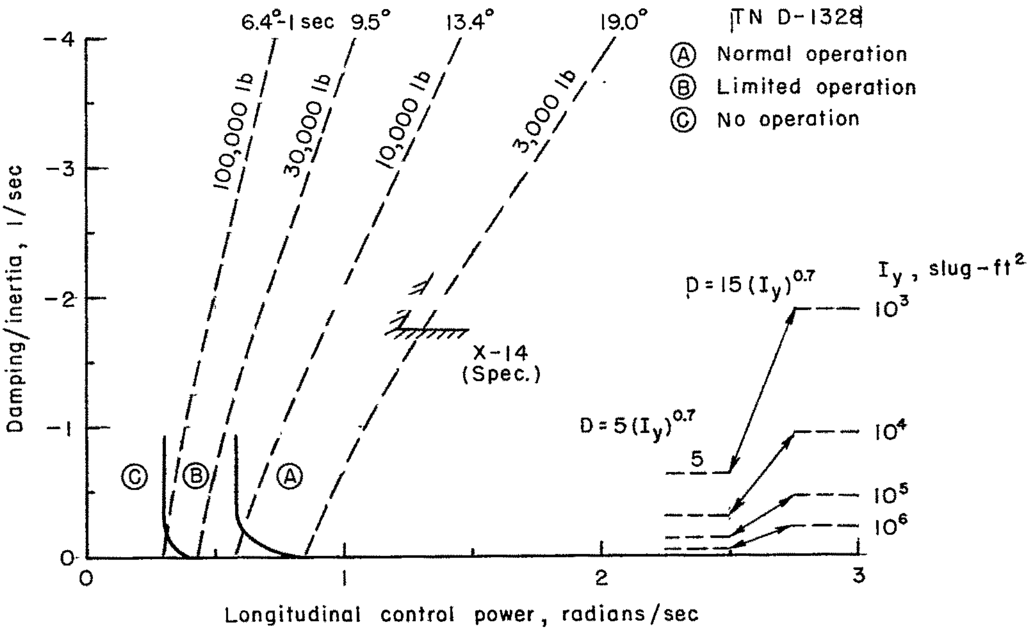

Figure 4.— Comparison of flight test results with MIL-H-8501A for the pitch axis.

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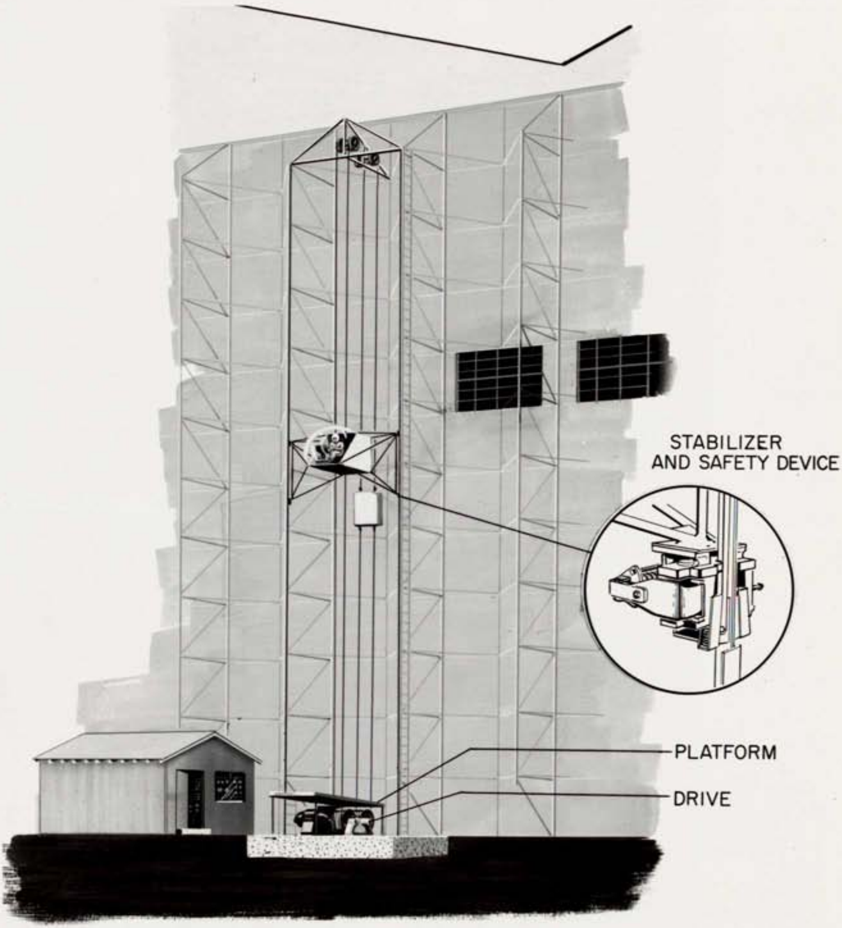

HEIGHT CONTROL TEST APPARATUS

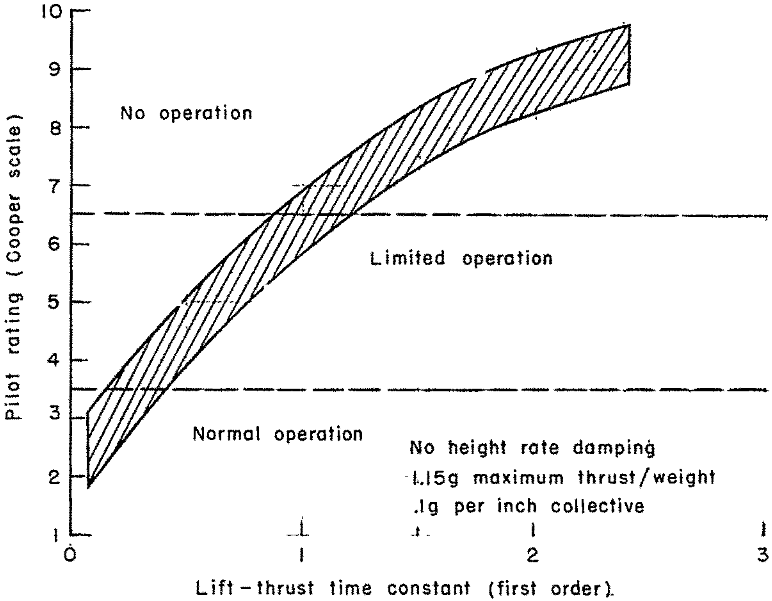

Figure 6.— Pilot opinion boundaries for the lift-thrust first order time constant with a motion simulator.

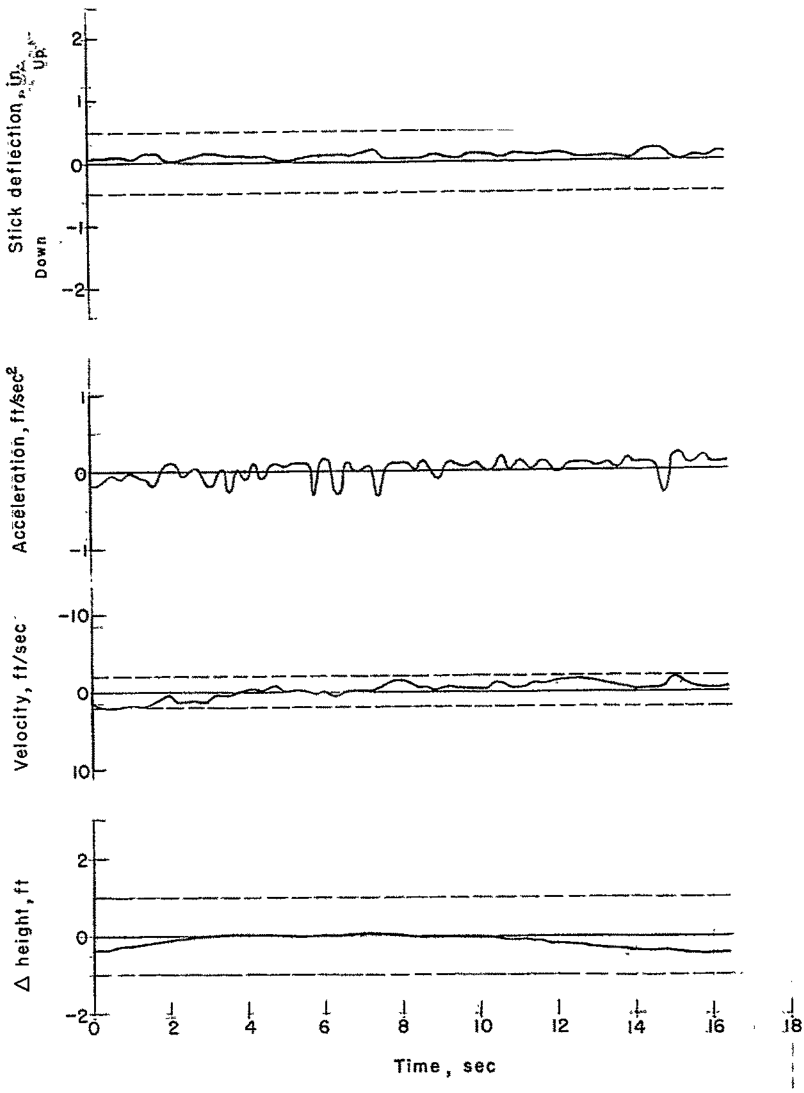

Figure 7.— Hovering steadiness results with variations in thrust response time constant.

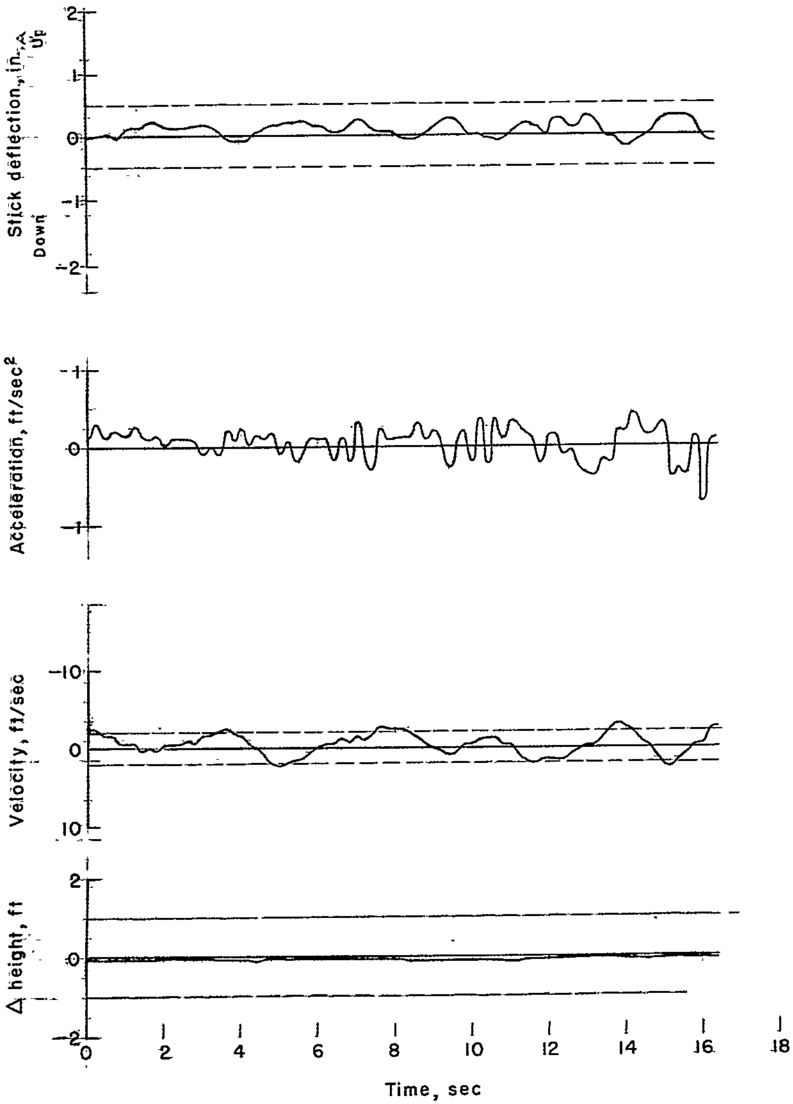

Figure 8.— Hovering steadiness results with variations in thrust response time constant.

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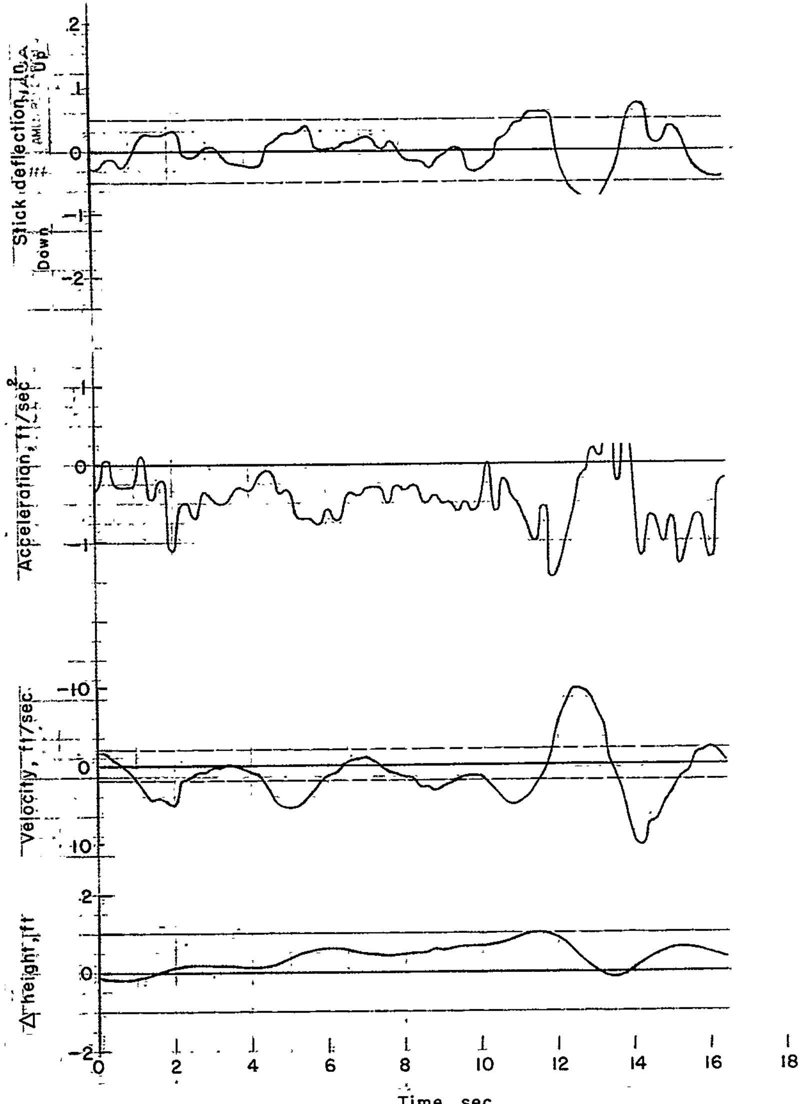

Figure 9.— Hovering steadiness results with variations in thrust response time constant.

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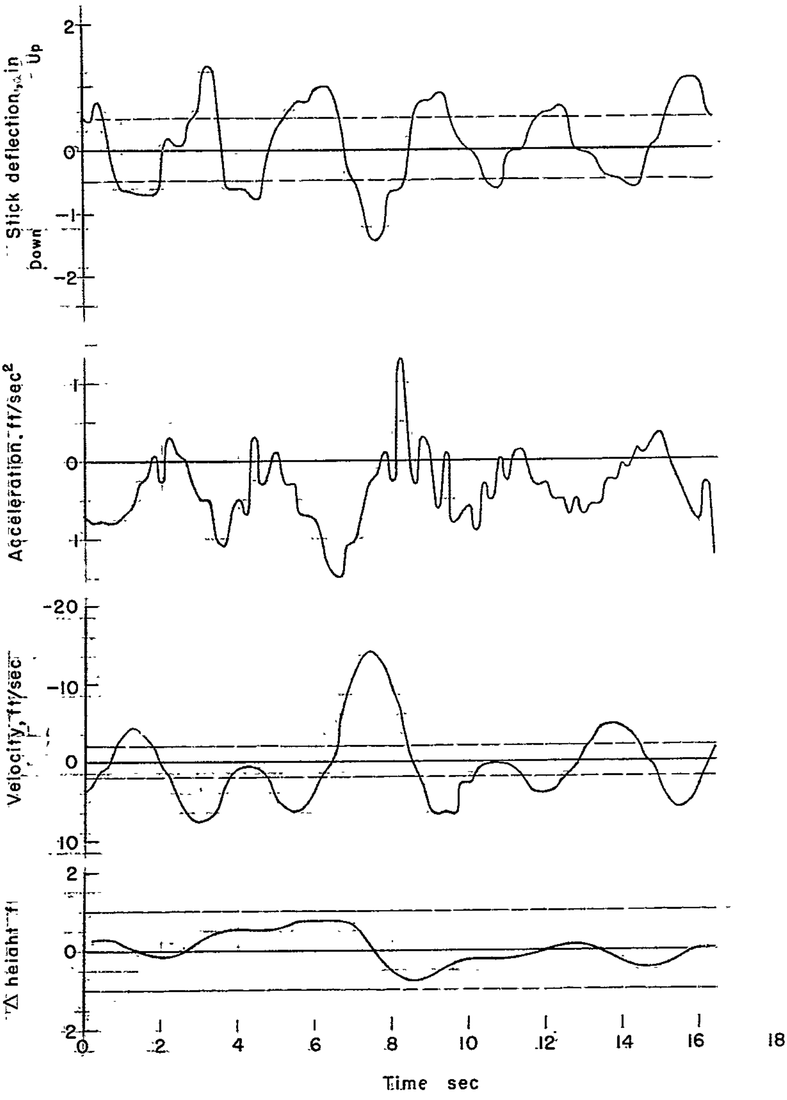

Figure 10.—Hovering steadiness results with variations in thrust response time constant.

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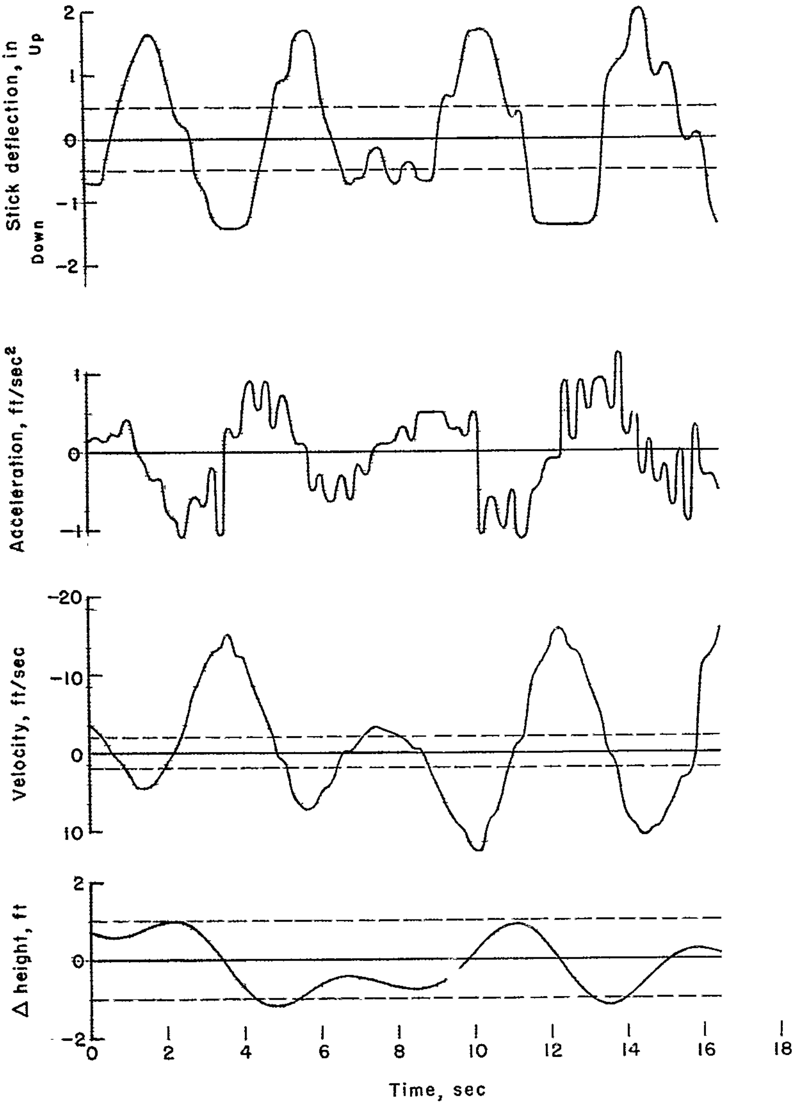

Figure 11.— Hovering steadiness results with variations in thrust response time constant.

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